

# **Comparison of Analytical Predictions and Experimental Results for a Dual Brayton Power System**

## **(Discussion on Test Hardware and Computer Model for a Dual Brayton System)**

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**Abstract.** NASA Glenn Research Center (GRC) contracted Barber-Nichols, Arvada, CO to construct a dual Brayton power conversion system for use as a hardware proof of concept and to validate results from a computational code known as the Closed Cycle System Simulation (CCSS). Initial checkout tests were performed at Barber-Nichols to ready the system for delivery to GRC. This presentation describes the system hardware components and lists the types of checkout tests performed along with a couple issues encountered while conducting the tests. A description of the CCSS model is also presented. The checkout tests did not focus on generating data, therefore, no test data or model analyses are presented.

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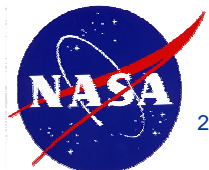
## **(Discussion on Test Hardware and Computer Model for a Dual Brayton System)**

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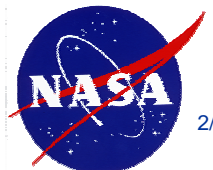
# Acknowledgement

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The author would also like to thank Bob Fuller of Barber-Nichols.

# Outline

- Introduction
- System
- Hardware and Operation
- Computer Model Description
- Status
- Conclusions

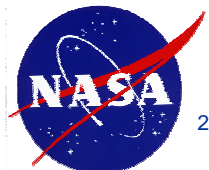


# Introduction

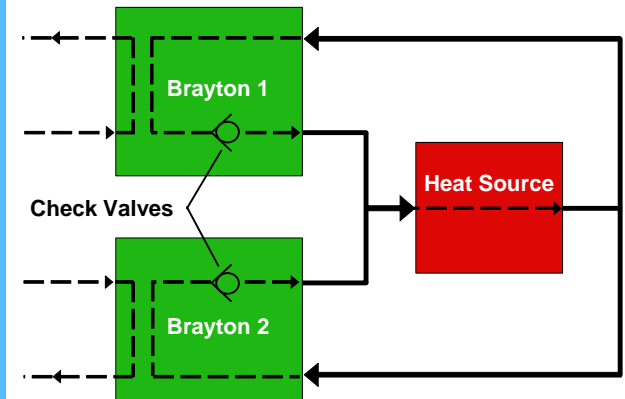
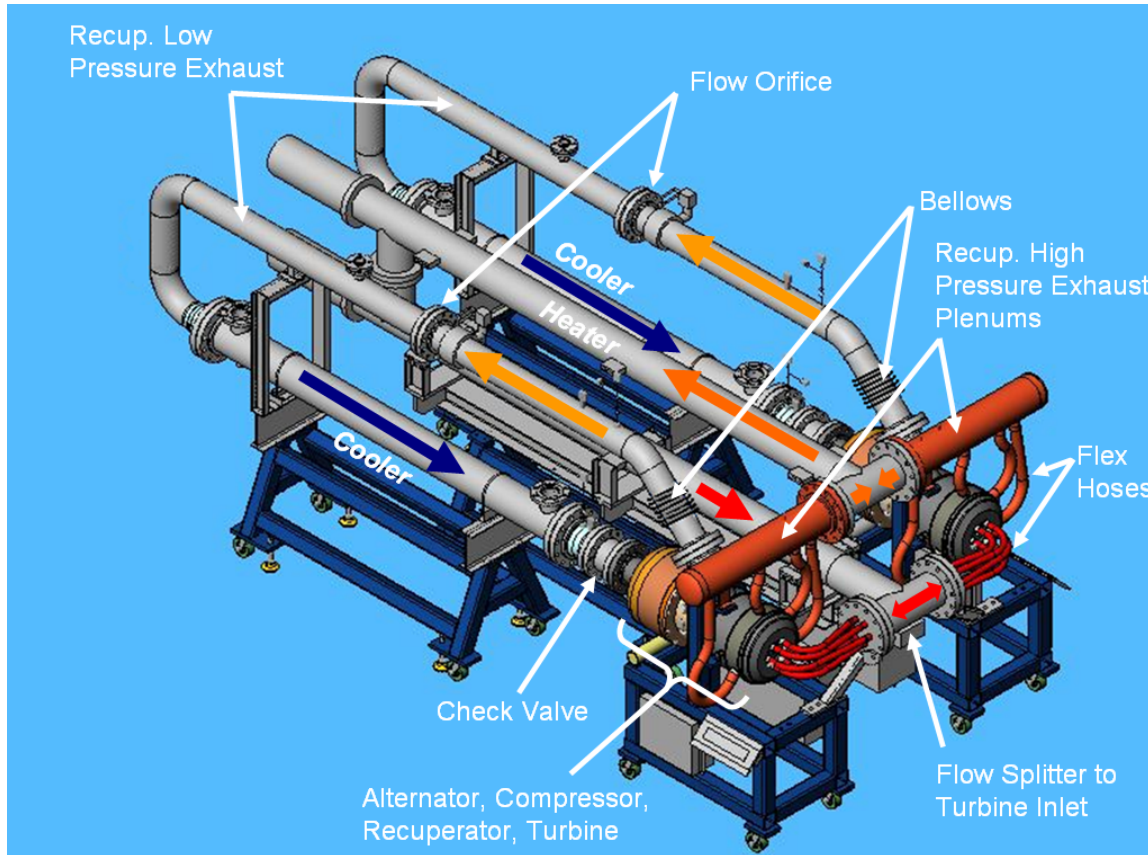
- Recent attention given to gas cooled reactors for potential space power applications
  - No existing hardware to evaluate effect of redundant power conversion units coupled to a gas reactor
  - Experimental studies deemed critical to proof of concept
  - NASA Glenn Research Center contracted for system design and fabrication with Barber-Nichols, Arvada, CO
- A single CBC test loop very similar to this system already exists
  - Also built by Barber-Nichols
  - Resides at Sandia National Laboratories (SNL) and tested by Dr. Stephen A. Wright
- The dual system is unique because it employs two CBC units sharing a common gas inventory and common heat source
  - Working fluid free to redistribute between the two CBC loops as system operation dictates
  - Hardware not flight-like, but sufficient for demonstrating the proof of concept
- Operational areas of interest
  - CBC units at different shaft speeds
  - One CBC unit while the other is standby (i.e. it is off)
  - Starting the CBC units in both staggered and simultaneous fashion
- Parallel computer model development done in Closed Cycle System Simulation (CCSS) design and analysis tool
  - Will be used for pretest predictions and posttest validation
  - Can be employed to make informed decisions for designing future systems

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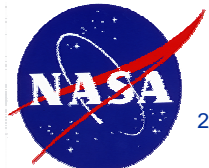


# Dual Brayton System



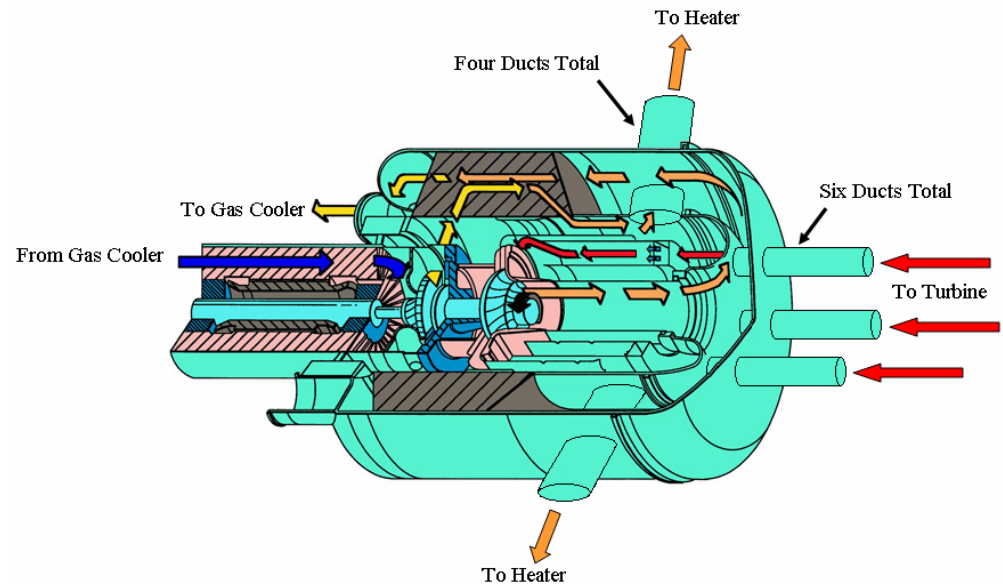
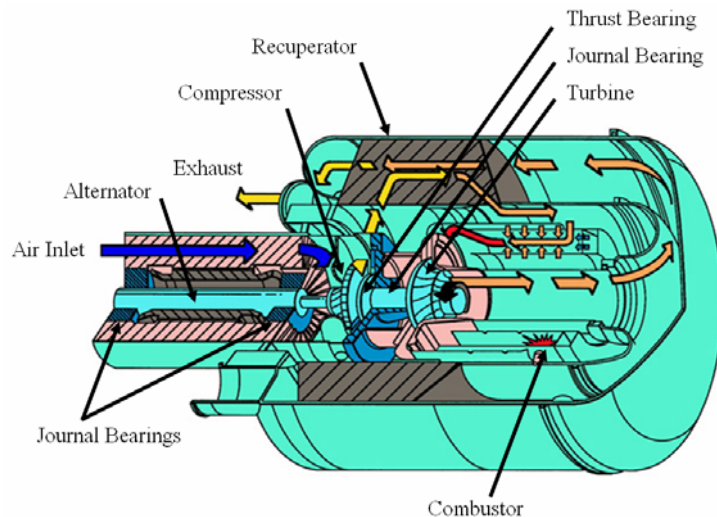
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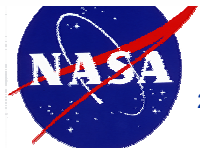
# Modified Capstone C-30

- Centered the design around a modified Capstone Model C-30 commercial microturbine
  - 30 kWe, air-breathing converter
  - Comprises alternator, compressor, recuperator, and turbine
  - Added 4 ducts from recuperator high pressure exit to heater inlet
  - Added 6 ducts from heater exit to turbine inlet



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# Gas Cooler

- Basco/Whitlock gas-to-liquid heat exchanger
- Shell and tube design
  - Gas flows through 70, 0.5 in. I.D. tubes
  - Water flows through shell side, 8.0 inch I.D.
  - 114 inches long (9.5 ft)



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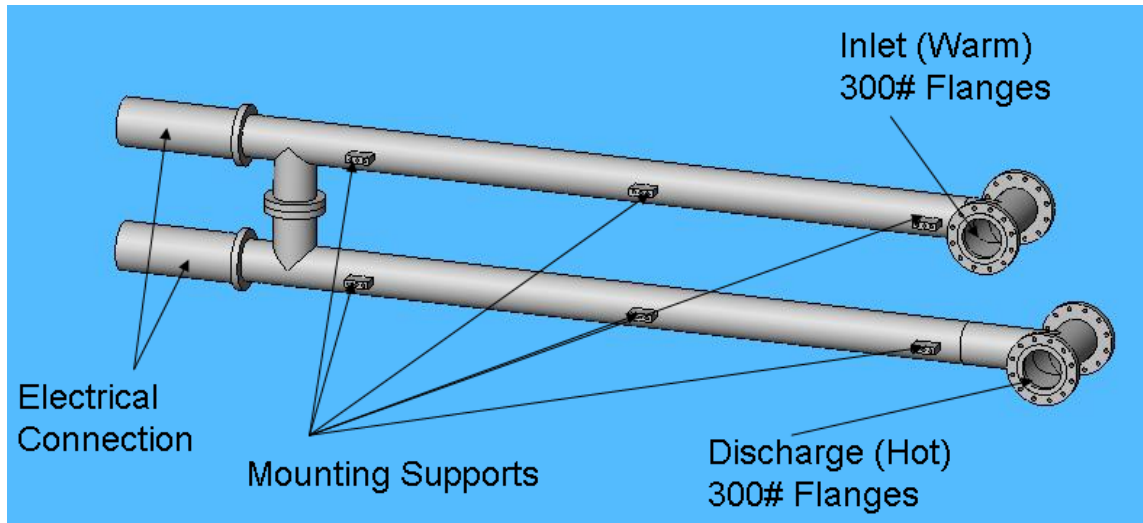
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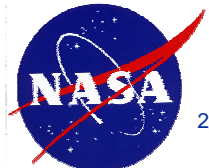
# Heater

- Only component shared by the two Brayton loops
- Chromalox – custom built, 180 kW-rated electric resistance heater
  - Maximum achievable gas temperature of 1000 K (Capstones designed for 1144 K)
- Similar to that of a shell and tube heat exchanger
  - 48 heating elements (Incoloy 800) act as the tube portion, 0.475 in. O.D.
  - Series of baffles persuades the gas working fluid across the tubes in the shell portion, 7.98 in. I.D.
  - ~ 300 inches long (25 ft)
- Anticipated 2-3 psi pressure drop at design speed



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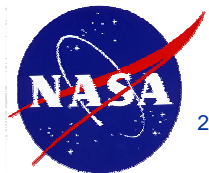
# Assembled Hardware

- The modified Capstone C-30 units, gas coolers, and heater were assembled to form the dual Brayton test loop
- The entire system is 19 feet long, 10 feet wide, and 8 feet high



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# System Operation

- Operation requires only a few user control inputs
  - Heat input, heat rejection, and an electric load
- Heater set to maintain a specific power or exit temperature
  - Only one turbine inlet temperature is allowed – one heater
- Waste heat is rejected to the facility water running through the gas cooler
  - Supply temperature is relatively constant for a given day
  - Manual valve is used to control the flow rate of the water
- Retained the Capstone commercial controller, which uses a parasitic load to maintain a set shaft speed
- Computer interface sends command signals to a central controller which communicates with Capstone and heater controllers
- Each CBC loop can be operated at different shaft speed set points
- Certain safeguards in place
  - Capstone controller will not let the shaft over speed
  - Burst disc on each Brayton loop in case of over pressure
  - Heater controller monitors sheath material temperature
  - On-screen warning if compressor inlet pressure is low
  - System shutdown if coolant flow is lost

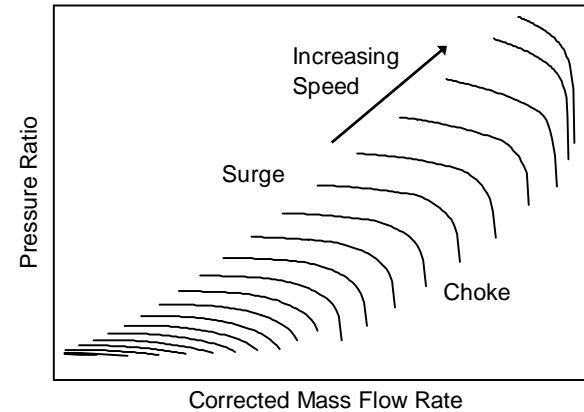
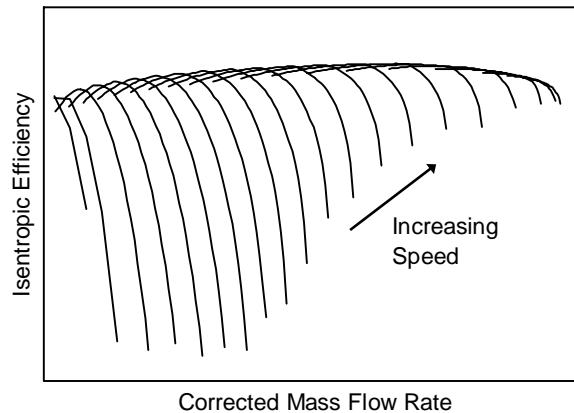
# Computer Model

- Closed Cycle System Simulation (CCSS)
  - Numerical Propulsion System Simulation (NPSS) environment
  - Used previously in analytical studies and test hardware performance studies
  - Modeled a flight-like, 2kW Brayton power conversion unit tested at NASA GRC
- Operated in three separate modes: design, off-design, and transient
  - Design
    - Hardware geometries are known and coded into the model setup
  - Off-design
    - Steady-state solutions
    - Vary shaft speed, heater power, turbine inlet temperature, coolant flow rate, gas inventory, etc.
  - Transient
    - Material temperatures become time-dependent
    - Turbomachinery is assumed to operate in a quasi-steady-state mode
- Solver handles 177 independent variables
  - Most of the variables are hardware material temperatures
  - Drive the system to equilibrium
    - All heat transferred is accounted for
    - Sum of the pressure drops/rises around the loop must be zero
    - System gas inventory distributed as necessary

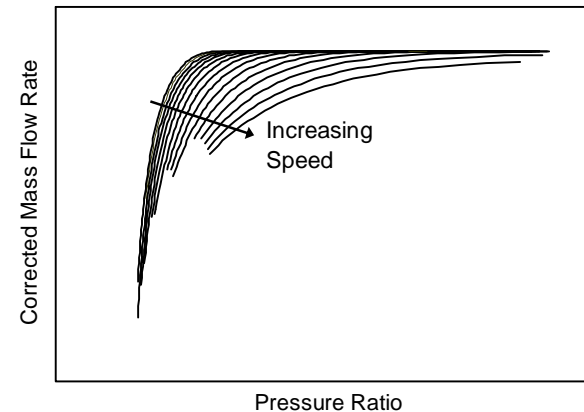
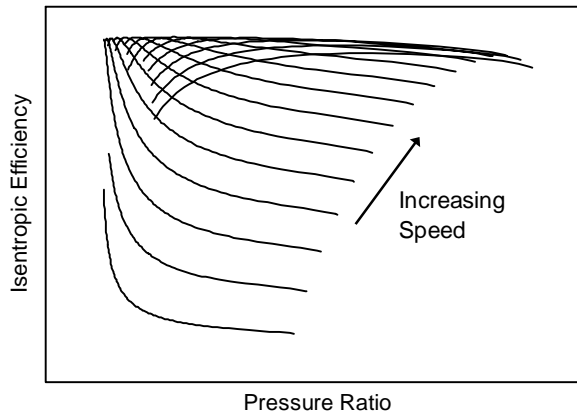
# Turbine and Compressor Models

- Compressor performance map generated in CCOMP (Centrifugal Compressor Off-Design Program)
  - 10 to 105% design speed
- Turbine performance map generated in RTOD (Radial Turbine Off-Design) program
  - 10 to 155% design speed

Compressor

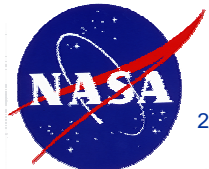


Turbine



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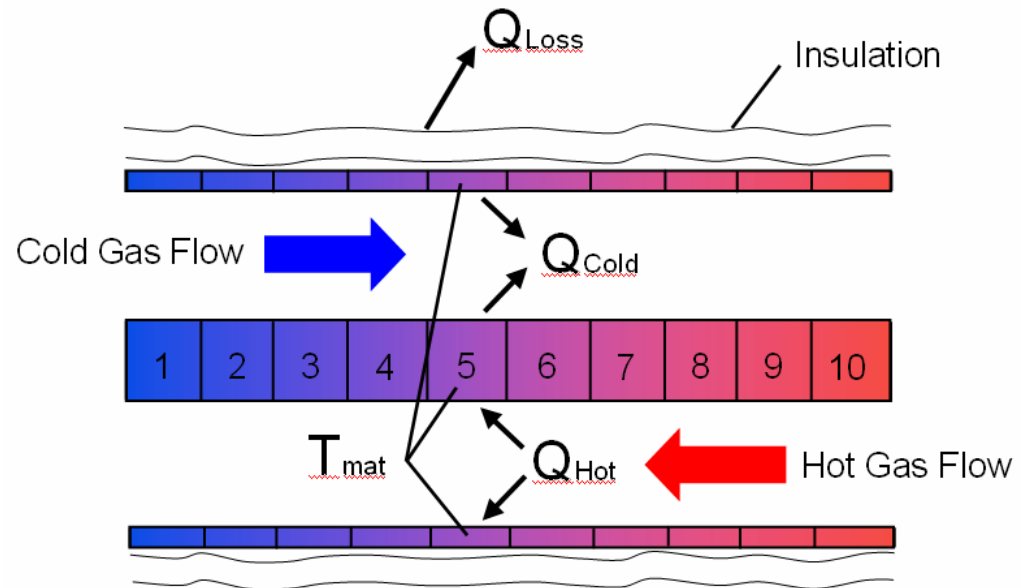


# Recuperator Model

- Gas-to-gas, offset strip-fin, counter flow heat exchanger ~ 78% effective
- Kays and London heat transfer and friction factor coefficients
- Structure is divided into ten nodes – stainless steel
- Heat loss across the insulation is always calculated as steady-state

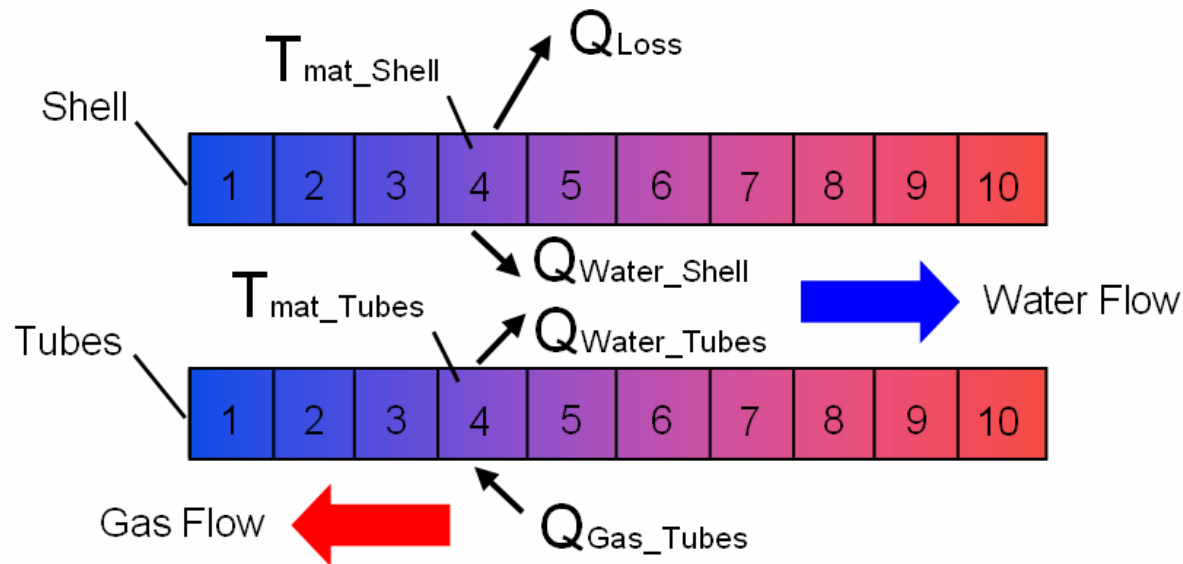
$$\dot{Q} = h_c A (T_{mat} - T_{fluid})$$

$$\frac{dT_{mat}}{dt} = \frac{Q_{in} - Q_{out}}{m_{mat} C_{mat}}$$



# Gas Cooler Model

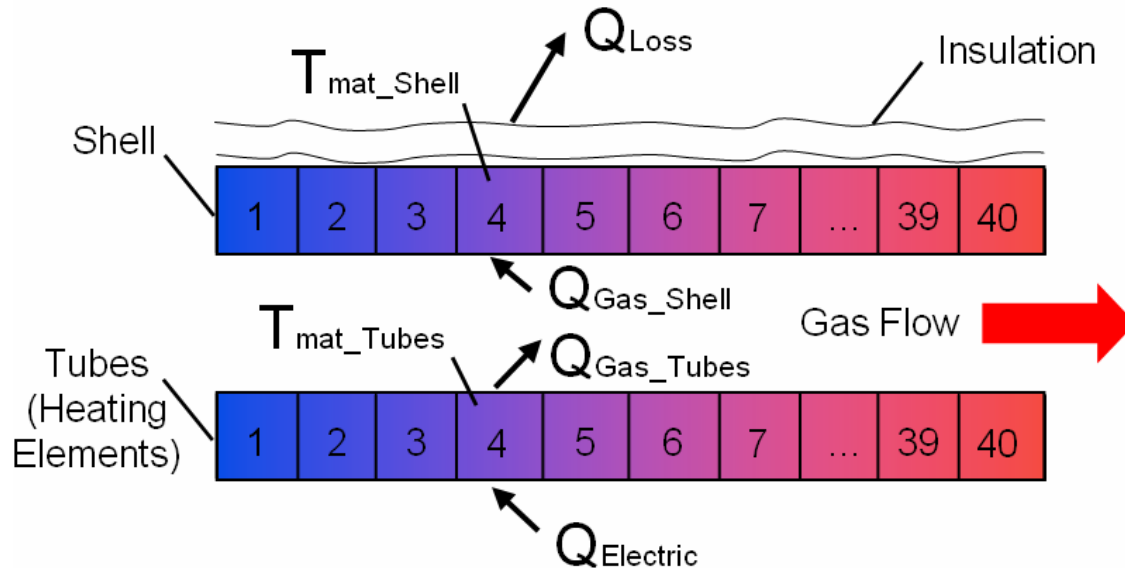
- Shell-and-Tube, gas-to-water heat exchanger
- Circular pipe flow correlations for heat transfer and friction factor coefficients
- Structure is divided into ten nodes – stainless steel tubes, carbon steel shell
- Heat loss to ambient air, but no insulation





# Electric Heater Model

- Shell-and-Tube like electric resistance gas heater
- Modified circular pipe flow correlations for heat transfer and friction factor coefficients
- Structure is divided into forty nodes – Incoloy 800 heating elements, stainless steel shell
- Heat loss across the insulation is always calculated as steady-state



# Status

- Checkout tests performed at Barber-Nichols
  - Individual units ran as single loop with second unit blanked
  - Staggered and simultaneous dual system startups
  - Ran dual system at equal and unequal speeds
  - Heater power limited at Barber-Nichols facility
- Current issues with system hardware
  - Internal flow leakage in the Capstone units
    - Recuperator HP exit to turbine inlet/exit
    - Recuperator bypass flow at housing
    - Resolved through installation of internal manifold
  - Heater pressure drop much greater than design specification
    - Anticipated 2-3 psi drop, measured >3 psi at half speed, estimate >10 psi at full speed
    - Working with Chromalox to resolve the issue
    - Proposed solution to reduce number of internal baffles
- Expected delivery to Glenn early Spring

# Conclusions

- Built a dual closed-Brayton-cycle system with common heat source and common working fluid
- Demonstrated the ability to startup and shutdown units independently
- Demonstrated operation with speed imbalance
- Need to resolve heater pressure drop issue
- Will compare test data to model analysis